LEVEL ROAD ACCELERATION, FUEL CONSUMPTION, AND STEADY-PULL EVALUATIONS USING DF-2 AND JP-8 FUELS

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By

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Limited evaluations were conducted on the M998 High Mobility Multipurpose Wheeled Vehicle (HMMWV) and the M977 Heavy Expanded Mobility Tactical Truck (HEMTT). The data that these evaluations would yield included startability and idle quality, acceleration rates, and fuel consumption. The previously tested M88A1 Medium Recovery Vehicle was also evaluated. However, these evaluations would determine if a Teledyne Continental Motors-recommended fuel injection and metering pump adjustment would increase performance and allow the engine to achieve its rated horsepower. As a result of these evaluations, it was determined that the conversion to JP-8 from DF-2 increased the acceleration time of both the M998 and M977 vehicles. Also, the fuel consumption increased on both vehicles; however, the increases were below that predicted by the heating value difference between the two fuels. The M88A1 exhibited an increase in power while pulling its own weight after the pump adjustment; however, the power increase was not noticeable while towing the M1A1 tank.

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EXECUTIVE SUMMARY

Problems and Objectives: When the U.S. Department of Defense issued Directive No. 4140.43, Fuel Standardization in March 1988, JP-8 (NATO Code F-34) was chosen to replace VV-F-800 DF-2 (NATO Code F-54) in all combat and tactical vehicles throughout NATO. Due to JP-8's lower energy content per gallon than DF-2, engine power loss and increased fuel consumption were expected. The effects of JP-8 fuel on fuel consumption and acceleration were unknown. A limited test program was conducted in 1988 on selected vehicles to provide initial data to quantify the effects of using JP-8 fuel. The M998 and M977 vehicles, although selected, were not available during the initial testing. Also, during this limited testing, it was discovered that the M88A1 medium recovery vehicle exhibited an engine power loss and fuel consumption higher than expected based on the difference between JP-8 and DF-2. The engine manufacturer for the M88A1 recommended an injection pump adjustment that would recover the vehicle's power loss with JP-8. This program was conducted to determine the effects of using JP-8 fuel on the two remaining high-density vehicles, and to evaluate the effect of the recommended pump adjustment on the M88A1 vehicle.

Importance of Project: Although previous demonstration programs had verified that JP-8 can be successfully used in diesel-burning vehicles and equipment, it was important to quantify the performance of the two highest density vehicles in the inventory, while using JP-8 fuel. The evaluation of the M88A1 with the recommended fuel pump adjustment can have an impact in the manner the Army approaches the M1A1 tank recovery problem.

Technical Approach: The vehicles for this limited testing program were selected based on density, engine type, and mission profile. Tests were performed in the M998 and M977 vehicles to determine fuel consumption and acceleration time differences using diesel fuel and JP-8 fuel. Tests on the M88A1 would determine fuel consumption and towing speed differences using diesel fuel and JP-8 fuel before and after a recommended fuel pump adjustment to regain power loss with JP-8 fuel.

Accomplishments: It was determined that the use of JP-8 increased the acceleration times on both the M998 and M977 vehicles. There was a 2-percent increase in fuel consumption for both vehicles except during the 48-km/hr evaluation on the M998 that showed a 2-percent decrease. There was a noted improvement in fuel consumption and performance in the M88A1 vehicle in the nontowing mode; however, there was no improvement in towing speed after the fuel pump adjustment. Towing speeds were lower with JP-8 in both cases when compared to DF-2. There were significant increases in fuel usage (liter/km) and energy consumption (MJ/km) after the fuel pump adjustment.

Military Impact: The last of the high-density vehicles in the Army inventory have been evaluated and their performance quantified with JP-8 fuel. The data generated during these evaluations together with other data already available can be used to make the transition to JP-8 fuel.

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The authors would like to acknowledge personnel of the Maintenance Section, 6th Air Defense Artillery (ADA) Brigade; H Company, 3rd Squadron, 3rd Armored Cavalry Regiment (ACR); and the Component Repair Section, Directorate of Installation Support (DIS) Maintenance Division for their willing cooperation and assistance throughout the program. The authors would also like to acknowledge the technical support and guidance provided by BFLRF Director, Mr. S.J. Lestz, and the willing assistance provided by BFLRF Senior Technician, Mr. Greg Phillips, who was indispensable in conducting the tests. Special thanks are given to the BFLRF reports processing staff for its typing and editorial assistance.

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I. INTRODUCTION

In 1988, a limited series of tests was conducted in an attempt to quantify the fuel consumption and acceleration time differences resulting from the use of DF-2 and JP-8 fuels.(1)* The vehicles tested included the M1009 Commercial Utility Cargo Vehicle (CUCV), M928 5-ton truck, M113A2 personnel carrier, M88A1 medium recovery vehicle, and M1A1 main battle tank. The selection of vehicles for testing was based on equipment density, engine type, and mission profile. The M998 High Mobility Multipurpose Wheeled Vehicle (HMMWV) and M977 Heavy Expanded Mobility Tactical Truck (HEMTT), although selected in the initial series of tests, were not available for testing. During the initial series of tests, the M88A1 recovery vehicle powered by the AVDS-1790-2DR engine exhibited a higher than expected fuel consumption and power loss. Teledyne Continental, manufacturer of the AVDS-1790-2DR engine, recommended a field adjustment to the fuel injection and metering pump that would recover the power loss exhibited when operating with JP-8 fuel.(2) Consequently, the evaluations covered in this report were conducted to quantify the fuel consumption and acceleration time differences between Diesel Fuel, VV-F-800D DF-2 (3) and Aviation Turbine Fuel, MIL-T-83133 JP-8 (4) on the M998 and M977, the two remaining high-density vehicles in the Army's inventory, and to reevaluate the power difference on the M88A1 after the recommended fuel pump adjustment. Testing was conducted at Ft. Bliss, TX. The 6th Air Defense Artillery (ADA) Brigade provided vehicles and crews for the M998 HMMWV and M977 HEMTT vehicles, while the 3rd Armored Cavalry Regiment (ACR) provided the M88A1 recovery vehicle and the M1A1HA (Heavy Armor) main battle tank.

II. BACKGROUND

The JP-8 conversion initiative resulted from a Tactical Air Command Required Operational Capability request in 1967 for a safer jet fuel. A proposed conversion from JP-4 to JP-8 for aircraft within North Atlantic Treaty Organization (NATO) nations to increase safety, reduce vulnerability, extend operating range, and enhance commercial availability was introduced in

* Underscored numbers in parentheses refer to the list of references at the end of this report.

1976. However, because of questions on cold startability of helicopters, increased fuel price differential, and concerns about fuel availability during wartime operations, the conversion process was delayed during the late 1970s since nations were reluctant to ratify this conversion until all issues had been resolved.

With the 1981 introduction of the M1 tank in Germany, JP-5 or JP-8 were blended with NATO standard diesel, F-54, to solve a severe low-temperature fuel-waxing problem. The procedure was successful, and it became policy that all fuel during winter would be blended prior to exiting the Class III supply points.

A United States published report entitled "JP-8 and JP-5 as a Compression-Ignition Engine Fuel," (5) in 1985 confirmed the feasibility of using JP-8 in lieu of F-54 diesel fuel; in 1986, HQ Army Materiel Command acknowledged acceptability in using JP-8 as an alternate fuel. NATO countries agreed to convert from NATO No. F-40 (JP-4) to F-34 (JP-8) effective 01 January 1987.

With this planned conversion, the concept of a Single Fuel on the Battlefield became a reality with significant logistical and operational advantages. Limited testing of M88A1, M1A1, M113A2, M1009, and M928 vehicles at Fort Bliss assessed fuel consumption, acceleration times, and hot starting limitations with JP-8 fuel. The JP-8 Demonstration Program was initiated at Ft. Bliss on 01 February 1989 (6) and, in August 1990, the Department of Defense (DOD) implemented the Single Fuel on the Battlefield concept by providing Jet A-1 (i.e., JP-8 fuel without its three additives) for U.S. forces in Operations Desert Shield/Storm.

III. OBJECTIVES

One objective of these evaluations was to quantify performance and fuel consumption on the two remaining high-density tactical vehicles in the inventory when converting from DF-2 to JP-8 fuel. A second objective was to reevaluate and quantify the M88A1 recovery vehicle full-power performance and fuel-consumption changes when operating with JP-8 fuel in lieu of diesel DF-2

fuel and to quantify power loss recovery with JP-8 fuel after a Teledyne Continental-recommended field adjustment to the M88A1 fuel injection and metering pump.

IV. APPROACH

BFLRF coordinated the evaluation of the selected vehicles with the Directorate of Installation Support (DIS), the Logistics Assistance Office (LAO), and the Logistics Sections of the 3rd ACR and 6th ADA Brigade. A separate fuel supply system was fitted to the test vehicles to facilitate testing of the two fuels. A referee DF-2 fuel and the Ft. Bliss bulk issue JP-8 fuel were used for all testing. Instrumentation was installed to monitor various temperatures and to accurately measure the small amounts of fuel consumed during the evaluations.

V. DETAILS OF EVALUATION

A. Test Vehicles

The test vehicles were selected by local organizations tasked to support the evaluations. Several maintenance procedures were performed on the vehicles prior to the evaluations. On the M88A1 vehicle, track tension was adjusted, fuel filters were changed, and the fuel injection and metering pump was removed and recalibrated by DIS maintenance personnel. Transmission stall tests were performed, and fuel filters were changed in the M998 and M977 vehicles. No payloads or ballast loads were added to the test vehicles.

B. Test Site

The test site was selected by BFLRF personnel. Since the selected road had no weight restriction, both the wheeled and tracked vehicles were evaluated at the same site. The test track selected was a smooth hard-packed, gravel road running south-to-north. The roadway had a 5-percent south-to-north gradient.

C. Test Fuels

The Military Specification MIL-T-83133C, Grade JP-8 fuel used in the evaluations was obtained from the underground tanks of the units supplying the test vehicles. The DF-2 fuel was provided by BFLRF and was blended to meet requirements of Federal Specification VV-F-800D. Inspection properties of the fuels used in the evaluations (AL-19731-F, AL-19904-F, AL-17696-F) are given in TABLE 1.

TABLE 1. Inspection Properties of JP-8 and Reference No. 2 Diesel Fuel

		JP-8			DF-2	
Property	Method	MIL-T-83133C Requirements	AL-19731-F	AL-19903-F	VV-F-800D Requirements	AL-19657-F
Total Acid No., mg KOH/g	D 3242	0.015, max	0.007	0.003	NR*	ND**
Aromatics, vol%	D 1319	25.0, max	17.9	19.1	NR	ND
Olefins, vol%	D 1319	5.0, max	2.4	1.5	NR	ND
Sulfur, Total, mass%	D 4294	0.3, max	0.07	0.07	0.30, max	0.4
Distillation, °C	D 86					
Initial Boiling Point		Report	174	182	NR	214
10% Recovered		205, max	198	192	NR	240
20% Recovered		Report	201	197	NR	248
50% Recovered		Report	211	209	Report	268
90% Recovered		Report	237	236	357, max	318
End Point		300, max	256	262	370, max	351
Residue, vol%		1.5, max	1	1	3, max	1.5
Flash Point, °C	D 93	38, min	59.4	64	NR	ND
Gravity, °API	D 1298	37 to 51	43.3	43.3	NR	34.2
Density, 15°C, kg/L	D 1298	0.755 to 0.840	0.8091	0.8091	0.815 to 0.860	0.8535
Cloud Point, °C	D 2500	NR	<-50	<-45	Local	ND
Kinematic Viscosity, cSt, at	D 445					
40°C		NR	1.38	1.37	1.9 to 4.1	2.93
70°C		NR	0.97	0.96	NR	ND
Net Heat of Combustion,	D 240					
Btu/lb		18,400, min	18,420	18,503	NR	18,235
MJ/kg		42.8, min	42.845	43.038	NR	42.415
Btu/gal		NR	124,258	124,818	NR	129,765
Hydrogen, mass%	D 3178	13.4, min	13.77	13.98	NR	13.15
Existent Gum, mg/100 mL	D 381	7.0, max	1.2	0.6	NR	ND
Particulate Matter, mg/L	D 2276	1.0, max	0.4	1	10, max	0.6
Accelerated Stability, mg/100 mL	D 2274	NR	0.13	0.13	1.5, max	ND
Fuel System Icing Inhibitor	FED-STD-791, Method 5340	0.10 to 0.15	0.06	0.14	NR	ND
Corrosion Inhibitor, mg/L	HPLC	NR	NES†	11	NR	ND
Fuel Electrical Conductivity, pS/m	D 2624	150 to 600	80	130	NR	ND
Cetane Number	D 613	NR	48.4	46.1	45, min	ND
Cetane Index	D 976-80	NR	45.5	36.5	43, min	46.2
Visual Appearance	D 4176	Clean/Bright	Bright/Sed	Bright/Sed	Clean/Bright	ND
Colonial Pipeline Co. Haze Rating	Proposed	NR	1	1	NR	ND

* NR = No Requirement.
** ND = Not Determined.
† NES = Not Enough Sample.

D. Equipment and Installation

The following equipment was used in the evaluations:

- Fluidyne fuel flowmeter with digital timer/totalizer/indicator
- Day tank
- Fuel-to-air heat exchanger
- Eight-channel data logger
- Calibrated stop watches
- Fuel transfer pump
- External fuel tanks
- Metal stakes for markers

Premeasured fuel lines were fabricated from 13-mm (0.5-in.) steel braided high-pressure hose. A male pipe fitting at each end of the hoses permitted attachments to the quick disconnect and fittings of the different engines. The fuel flow transducer, day tank, digital totalizer, fuel filter, and data logger were mounted in a specially fabricated box with quick disconnects at the fuel inlet and outlet for easy installation on the test vehicles.

Fig. 1 illustrates the fuel supply system for the test vehicles. The fuels were supplied from separate external 114-liter (30-gallon) tanks securely strapped to the outside of the vehicles. A 12 VDC fuel pump capable of pumping 382 liter/hr (101 gal./hr) under 96.5 kPa (14 psi) was mounted at the fuel tank outlet to supply fuel to the systems. On the M88A1 recovery vehicle, an additional pump was installed at the day tank outlet to supply the fuel pressure required by the engine fuel system.

Thermocouples were attached to data-logging equipment, and measurements were taken during each test procedure. Thermocouples were installed in the following locations:

- Fuel into flowmeter and day tank
- Fuel from day tank to engine
- Fuel return from engine prior to heat exchanger
- Engine oil sump*
- Inside exhaust pipe at exit
- Cylinder head*

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* M88A1 recovery vehicle only.

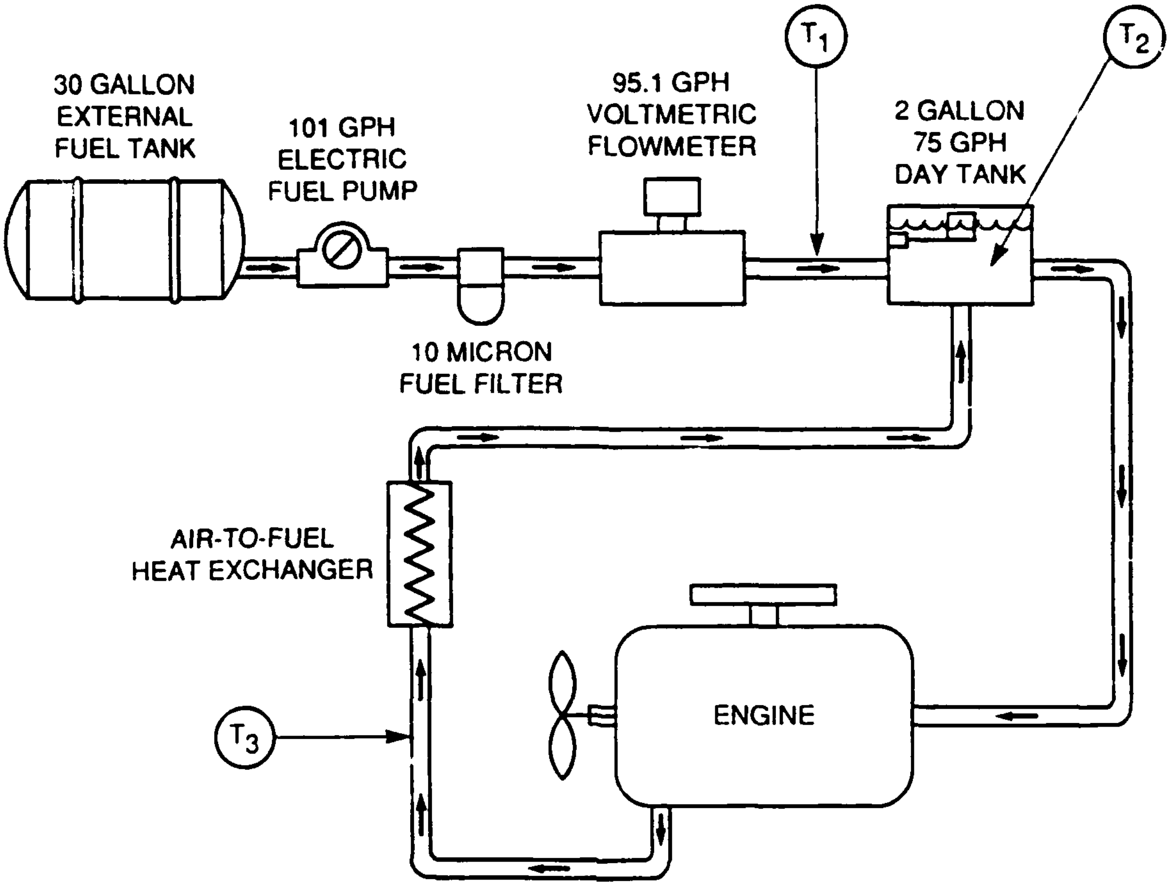

Figure 1. Illustration of fuel supply system for test vehicles

E. Acceleration Procedure

Wide open throttle accelerations from a standing start were performed on the M998 and M977 vehicles up to 48, 64, and 72 km (30, 40, and 45 miles) per hour. Six individual runs were performed with each fuel: three in each direction. The time in seconds was recorded for each speed. To stabilize engine temperature and performance, the vehicles were operated a minimum of 3218 meters (2 miles) at normal operating conditions after each three acceleration runs.

F. Fuel-Consumption Evaluation (All Vehicles)

Two stakes were placed at each end of a measured course [3218 meters (2 miles)] so that the stakes appeared aligned at the measurement point. With the transmission in high range, the

vehicle was accelerated at normal driving conditions until the desired speed was reached prior to the beginning marker. The approximate speed was maintained until both markers were cleared. Fuel measurement began when the observer was in line with the beginning markers and stopped when the markers aligned at the opposite end of the track. The vehicle was turned around, and the test was repeated with the vehicle traveling in the opposite direction. A total of four runs were made at each speed, two runs in each direction. All fuel-consumption volumes were corrected to volumes at 15°C (60°F).

For the towing mode evaluation of the M88A1 recovery vehicle, two stakes were placed at each end of a 3218-meter (2-mile) measured course so that the stakes appeared aligned at the measurement point. With the M1A1HA tank in tow, the M88A1 Recovery Vehicle was accelerated at full power, and maximum speed attained prior to reaching the beginning marker. Full power was maintained until both markers were cleared. Timing in seconds started when the observer was in line with the beginning marker and stopped when the markers aligned at the opposite end of the track. The vehicles were turned around and the test repeated with the vehicles traveling in the opposite direction. To prevent damage to the M88A1 recovery vehicle while towing, only one run, instead of two, was made in each direction.

VI. DISCUSSION OF RESULTS

A. Acceleration Times

The acceleration times of a given vehicle is a function of the work produced by the engine. The developed work and subsequent rate of work (power) are a function of the volume and energy content of the injected fuel. Injected fuel volume is a function of fuel density and viscosity, factors that affect the metering and leakage in a diesel injection system. The fuel energy density and the injected volume determine the energy content of the injected fuel. Combustion factors that determine power availability with a fuel are ignition delay and the thermal efficiency of the combustion and energy conversion processes. The aforementioned factors all contribute to the work and power development of an engine, which affect the vehicle acceleration times when a fuel conversion is made.

With the conversion from DF-2 to JP-8, several of the fuel properties (TABLE 1) that affect engine power potential vary. Typically JP-8 fuel is less dense with a lower kinematic viscosity. This lower viscosity results in a lower injected fuel volume than DF-2. A lower energy density with JP-8, combined with the lower injected volume, results in less chemical energy available for combustion and conversion at full rack. However, the lower cetane number of JP-8 results in slightly longer ignition delays and increased premixed combustion fraction, which leads to thermal efficiency improvements. All factors considered, the acceleration variations of a vehicle cannot always be projected simply based upon the fuel properties.(1)

The percent deviations in time-to-speed accelerations for the M998 HMMWV and M977 HEMTT, as a result of DF-2 to JP-8 conversion, are shown in Fig. 2. The M998 HMMWV utilizes a version of the General Motors 6.2L, normally aspirated, four-cycle, indirect injected, swirl chamber diesel engine. The M977 HEMTT utilizes a Detroit Diesel 8V-92T, turbocharged, two-cycle, direct injected, quiescent chamber diesel engine. Both the M998 and M977 vehicles experience longer acceleration times for the speed range evaluated when utilizing JP-8.

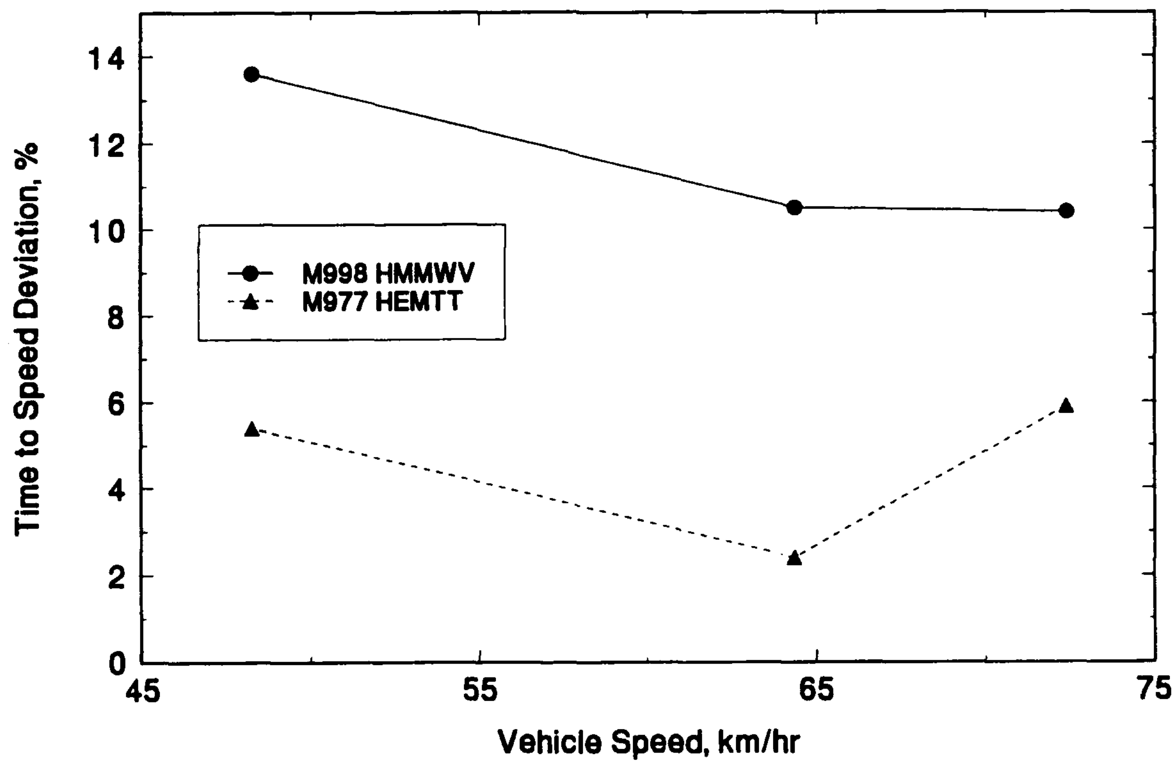

Figure 2. Vehicle time-to-speed accelerations — DF-2 to JP-8 conversion

The M998 HMMWV acceleration decrement is greater than that which would have been estimated from fuel property variations. The acceleration times-to-speed for the M998 vehicle are shown in Fig. 3. The error bars represent the 95-percent confidence interval of the average of the six evaluations for each fuel. The results indicate significant variability in the acceleration times regardless of the fuel utilized. Except for the time to 48 km/hr (30 mph), the error bars indicate the acceleration times are not significantly different at the 95-percent confidence level for the two fuels. The data also suggest the vehicle appears slower by a constant number of seconds at each speed. Previous evaluations (1) of a M1009 vehicle, which utilizes a version of the engine in the M998, revealed no acceleration penalty upon conversion to JP-8. The particular M998 utilized for the current evaluations had 565 km (351 miles) on the odometer at the beginning of testing. It can be speculated an incomplete engine run-in may have contributed to the greater than expected acceleration time variations.

The M977 HEMTT acceleration decrement is approximately that which would have been estimated from fuel property variations. The acceleration times-to-speed for the M977 vehicle are shown in Fig. 4. The error bars represent the 95-percent confidence interval of the average of the six evaluations for each fuel. The error bars indicate the acceleration times are not significantly different at the 95-percent confidence level for the two fuels. The data also indicate the variability in acceleration times was greater with JP-8 at the upper end of the speed range evaluated.

For a better understanding of the vehicle acceleration across the vehicle speed range, the rectilinear accelerations were calculated from the time-to-speed data. The deviations of the calculated accelerations due to the DF-2 to JP-8 conversion are depicted in Fig. 5. Both the M998 and M977 vehicles show slower accelerations at the low and high ends of the speed range evaluated. However, the mid-range accelerations with JP-8 are equivalent or faster than with DF-2 for the M998 and M977, respectively. From Fig. 6 of the rectilinear acceleration values for the M998, it is apparent the vehicle accelerates faster in the 48- to 64-km/hr (30- to 40-mph) range with either fuel. Fig. 7 for the M977 reveals the vehicle accelerates slower, with either fuel, as vehicle speed increases.

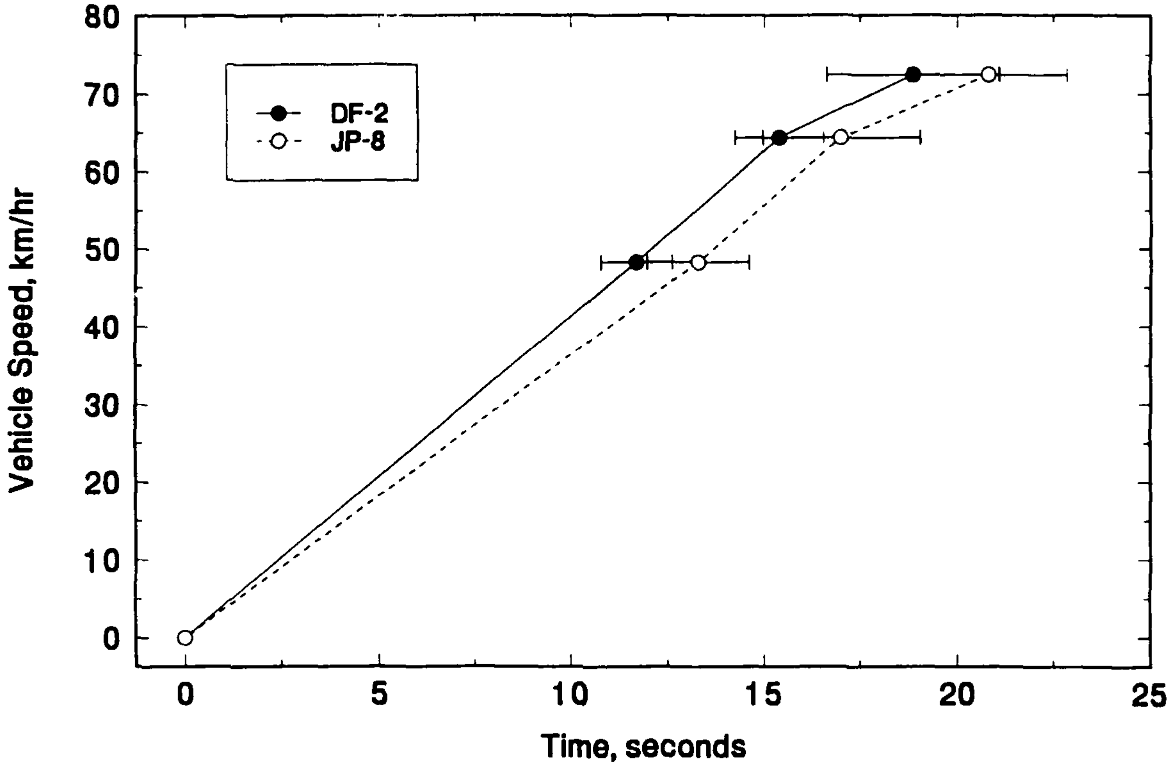

Figure 3. M998 HMMWV acceleration times

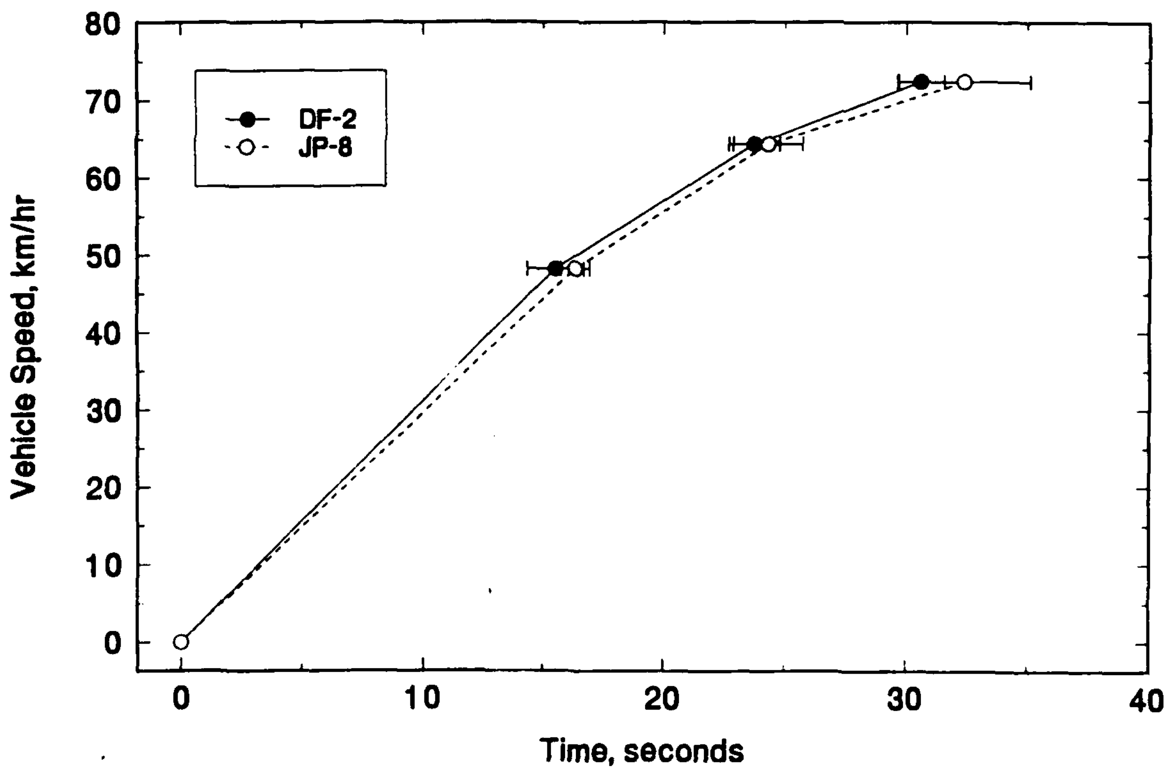

Figure 4. M977 HEMTT acceleration times

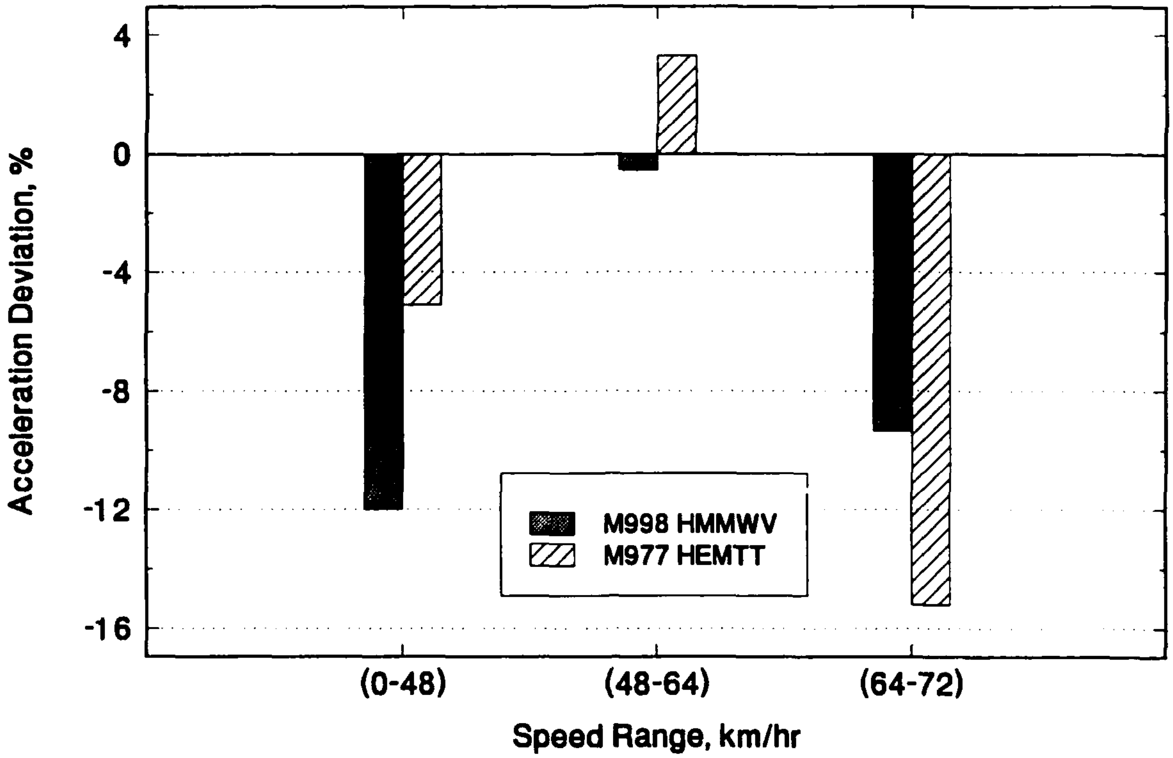

Figure 5. Vehicle rectilinear accelerations — DF-2 to JP-8 conversion

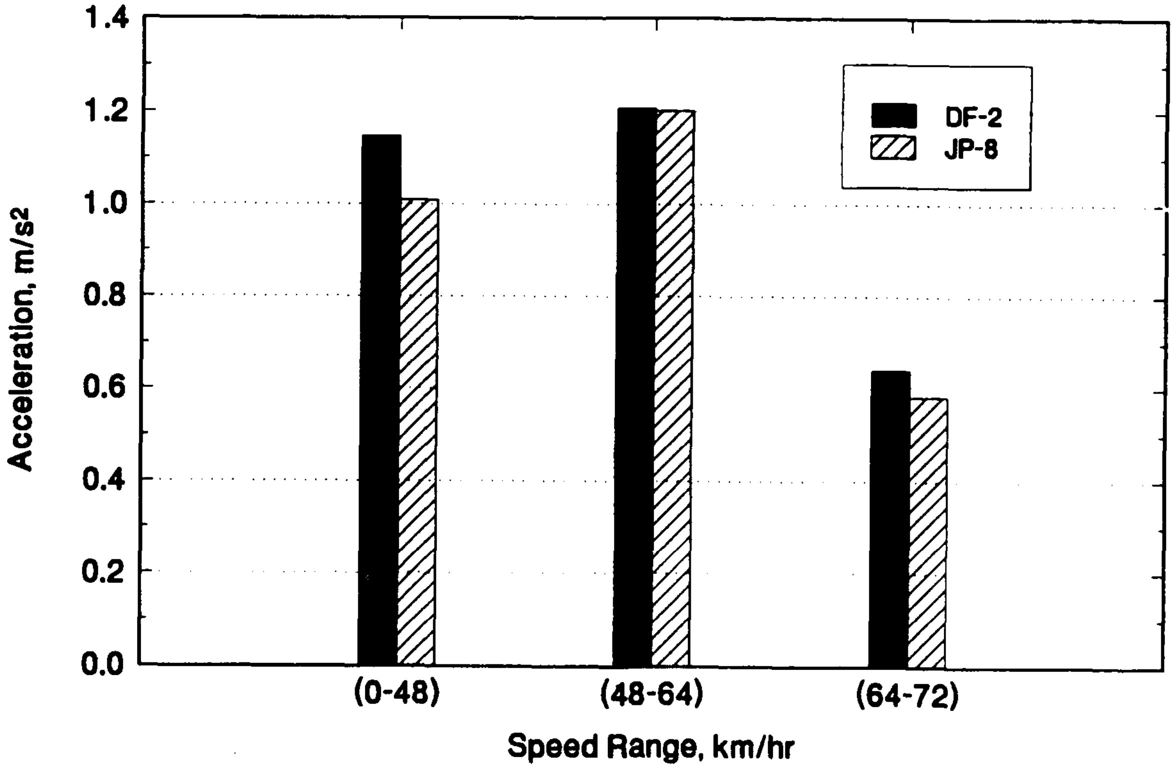

Figure 6. M998 HMMWV rectilinear accelerations

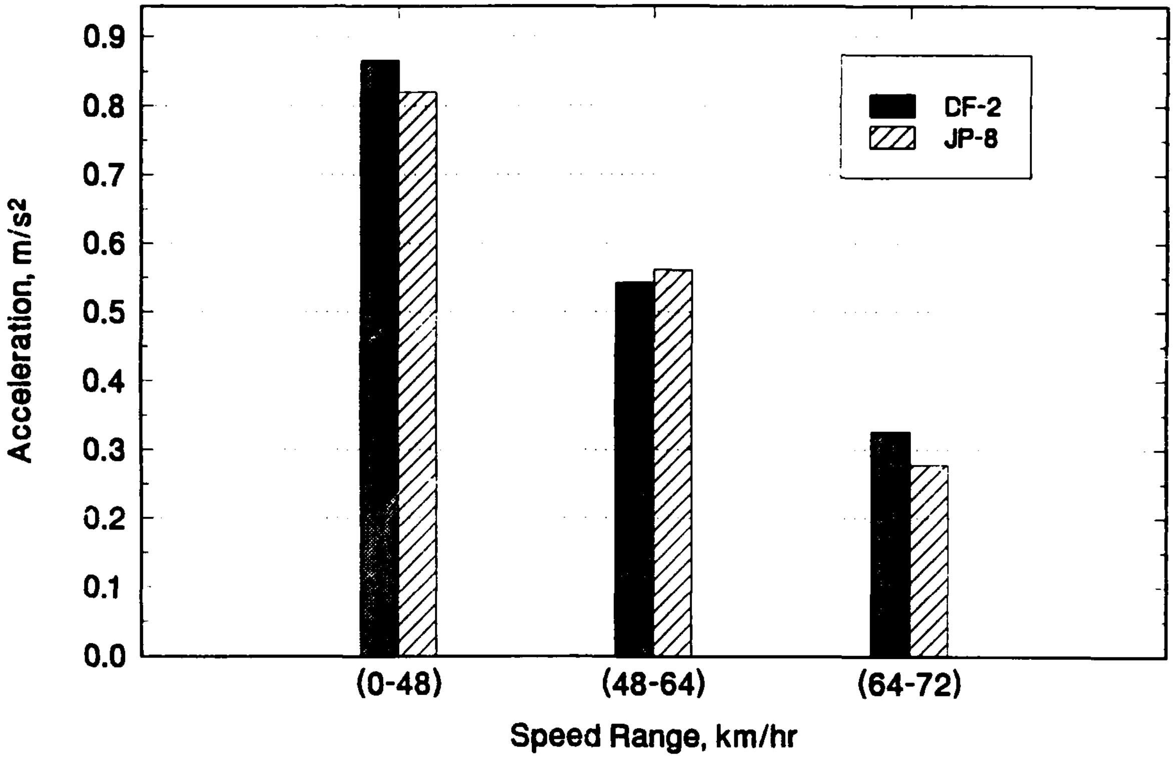

Figure 7. M977 HEMTT rectilinear accelerations

B. Fuel-Consumption Comparisons

The use of JP-8 should increase vehicle fuel consumption at road load conditions due to the heating value difference of the fuel. In general, JP-8 contains a lower unit of energy per volume quantity of fuel than does DF-2. Depending on how the engine thermal efficiency is affected by fuel composition, the actual difference in fuel consumption may fluctuate from the fuel consumption predicted on a volumetric heat of combustion basis. Alternatively, JP-8 induced reductions of maximum power and subsequent slower acceleration and lower maximum speeds may tend to reduce fuel consumption at full-load conditions. The steady-speed evaluations, which represent partial load conditions, were selected to obviate this effect.

The fuel-consumption measurements of these evaluations should not be considered representative of the fuel consumption obtained in actual service. The quasi-level road measurements obtained on these investigations will produce lower fuel-consumption levels than would be experienced during normal duty cycles where full-power accelerations and cross-country driving would occur.

The fuel-consumption deviations upon converting from DF-2 to JP-8 are shown in Fig. 8 for the M998 HMMWV. Also included with these data is the reference line denoting the volumetric heat of combustion difference between the test fuels, which, for these evaluations, was 4.16 percent. The data at each speed represent the average of four evaluations of fuel consumption for the 3218-meter (2-mile) test length. The fuel-consumption deviation at both speeds was less than expected from the heating value difference of the fuels. The error bands represent the 90-percent confidence intervals, based on the uncertainty in the DF-2 and JP-8 averages. Because of uncertainty in the fuel-consumption averages and the propagation of error, a 90-percent confidence interval was chosen as the level of significance of the fuel-consumption deviations. The fuel-consumption averages for both test fuels, and the 95-percent confidence intervals for each fuels average, are displayed in Fig. 9 for the M998 vehicle. Some variation in fuel consumption for the M998 could be attributed to the slight south-to-north grade of the test section. The evaluations were performed in both directions on the test section. The variation somewhat muddles the results of this evaluation, but it may trend the results toward actual operation. At a level of 90-percent confidence, it appears the fuel consumption of the M998 HMMWV while operating on JP-8 fuel is not significantly different than operating with DF-2 fuel for these evaluations.

Fig. 10 displays the fuel-consumption deviations upon converting from DF-2 to JP-8 for the M977 HEMTT. The reference line denoting the volumetric heat of combustion difference between the test fuels is also included. The data at each speed represent the average of four evaluations of fuel consumption for the 3218-meter (2-mile) test length. Again the fuel-consumption deviation at both speeds was less than would have been expected from the heating value difference of the fuels. The error bands represent the 90-percent confidence intervals, based on the uncertainty in the DF-2 and JP-8 averages. Again, because of the uncertainty in the fuel-consumption averages and the propagation of error, a 90-percent confidence interval was chosen to express the level of significance of the fuel-consumption deviations. The fuel-consumption averages for both test fuels and their 95-percent confidence intervals are displayed in Fig. 11 for the M977 HEMTT. Variations in fuel consumption for the M977 can be credited to the slight south-to-north grade of the test section. The fuel-consumption figures reflect the

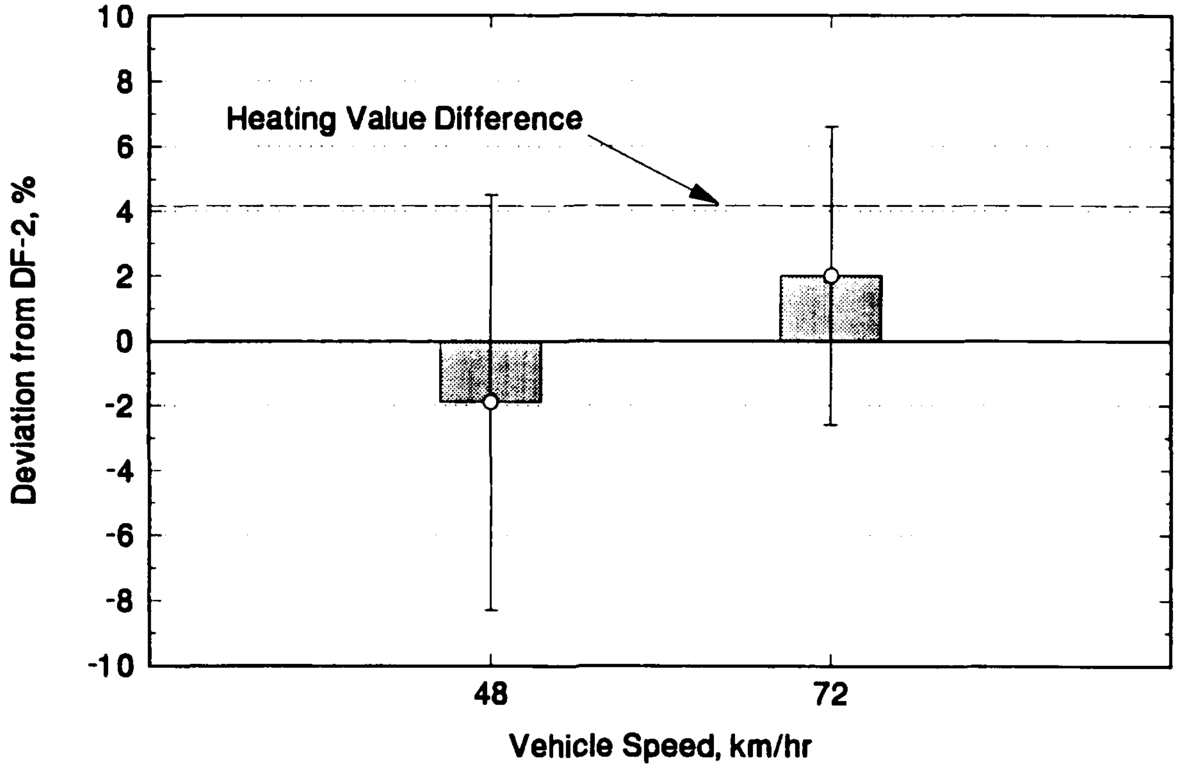

Figure 8. M998 HMMWV JP-8 fuel-consumption deviations

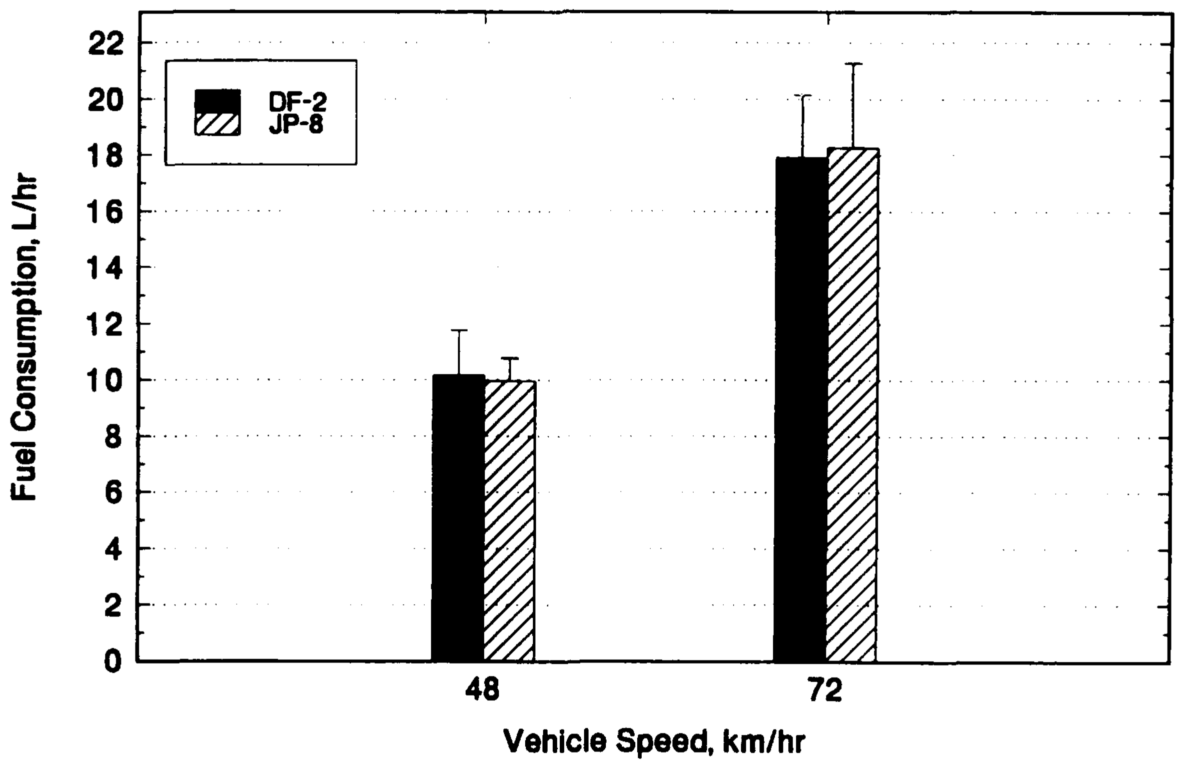

Figure 9. M998 HMMWV steady-state fuel consumption

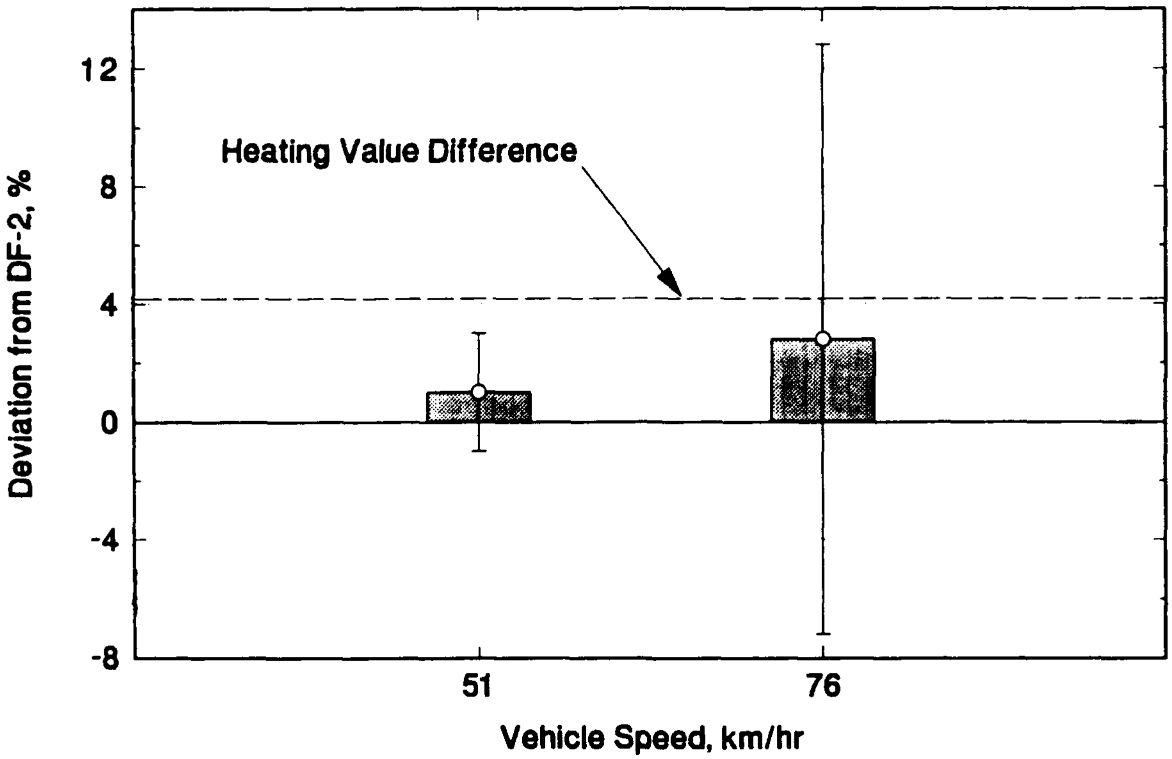

Figure 10. M977 HEMTT JP-8 fuel-consumption deviations

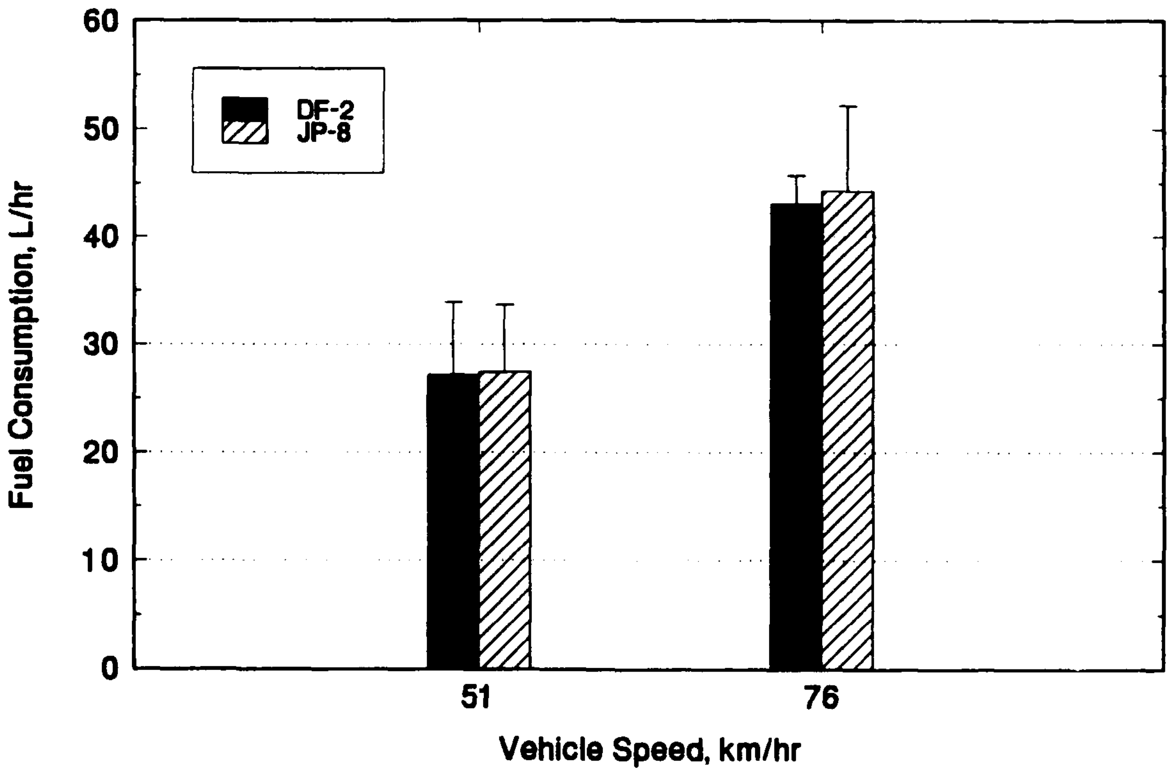

Figure 11. M977 HEMTT steady-state fuel consumption

direction in which the individual evaluations were performed. The M977 evaluations were also performed at the vehicle empty weight. The suspension stiffness at empty weight made it demanding for the operator to maintain a constant speed on the uneven and graded portions of the test section. The fuel-consumption variability effectively averages the terrain-induced effects on the vehicle fuel consumption. For these evaluations at 90-percent confidence, the fuel consumption of the M977 HEMTT while utilizing JP-8 fuel is not significantly different than operation with DF-2. However, a nominal increase of 2 percent appears to exist with JP-8 usage.

C. M88A1 Performance

1. Test Chronology and Pump Adjustments

The fuel injection pump was removed from the M88A1 recovery vehicle and calibrated to technical manual (TM) standards prior to any testing on the vehicle. The removal, calibration, and installation of the injection pump were performed by DIS maintenance personnel (general support level maintenance). TABLE 2 illustrates test stand fuel flow readings in cubic centimeters (cm^3) of the injection pump at several stages of calibration and adjustments. The precalibration readings were considerably higher than the calibration standards called for in TM 9-2910-34.(7) Unit maintenance personnel stated that a maintenance team from the Tank-Automotive Command had performed a field adjustment to the injection pump during Operation Desert Shield/Storm.

At the conclusion of the level road fuel-consumption and steady-pull evaluations with DF-2 and JP-8 fuel, maintenance personnel performed the on-vehicle adjustment to the fuel injection pump as specified in Teledyne Continental's Bulletin ER-88-222.(2) The vehicle, however, did not perform as expected after the adjustment. Instead of increased power, the vehicle exhibited a severe loss of power. Maintenance personnel attributed the power loss to injection pump timing; however, the reason for the power loss was never confirmed. The injection pump was removed from the vehicle and mounted on the test stand to ascertain the results of the fuel flow adjustment. The fuel flow readings indicated that the fuel flow was increased approximately

TABLE 2. Injection Pump Fuel Flow, cm^3

Calibration Settings, rpm	TM Standards, cm^3 per 500 Pump Strokes*	Precalibration Readings, After Removal From Vehicle	Initial Calibration Readings	Readings After Pump Adjustment	Second Calibration Readings, After Removal From Vehicle	Readings After Pump Adjustment
2440	100 to 102	128	101	114	101	107
2620	54 to 57	120	57	80	57	57
2750	0	118	0	12	4	5
1800	99 to 101	127	100	102	101	102
1000	80 to 85	120	78	79	79	80
150	>33	60	55	55	57	59
650	24 to 26	112	26	67	25	26

* Averaged fuel delivery for each injector.

13 percent at 2440 rpm, 7 cm^3 more than the expected increase after adjustment. The fuel injection pump was calibrated a second time, and the recommended adjustment performed with the pump on the test stand. Care was exercised to be as precise as possible on the adjustment. The expected 6 cm^3 fuel flow increase was obtained. The pump was reinstalled and testing resumed.

The level road, steady-pull (M1A1HA tow) evaluations before and after injection pump adjustment were performed on dry-surfaced roads. Also, the level road fuel-consumption evaluation after injection pump adjustment was conducted on dry-surfaced roads. The level road fuel-consumption evaluations with DF-2 and JP-8 prior to the fuel injection pump adjustment were conducted during precipitation on wet-surfaced roads.

2. Fuel Consumption

The fuel-consumption evaluations were performed on the 3218-meter (2-mile) test section having a slight south-to-north grade. Vehicle field evaluations have been traditionally performed in the summer months to maximize the vehicle performance deviations with JP-8 fuel. These evaluations were performed in the winter months at ambient temperature conditions that ranged from 4° to 8°C (39° to 46°F), and included precipitation. The effects of the precipitation and resultant deterioration of the test section increased the variation of the fuel-consumption data. For example, increased tractive effort to negotiate the muddy course at speed would be reflected as higher fuel consumption. Since military vehicles must operate in all types of terrain and weather conditions, the results may favor actual duty-cycle deviations with JP-8.

The combination of the grade variations and weather resulted in operator difficulties in maintaining steady-vehicle speeds. Therefore, the results of the four evaluations are presented as individual fuel-consumption rate and speed data sets. The fuel-consumption rate data shown in Fig. 12 are for a nominal vehicle speed of 24 km/hr [15 miles per hour (mph)]. The data indicate a higher fuel-consumption rate in the northerly direction because of the test section grade. The speed deviations for the M88A1 vehicle from the target 24-km/hr (15-mph) test speed

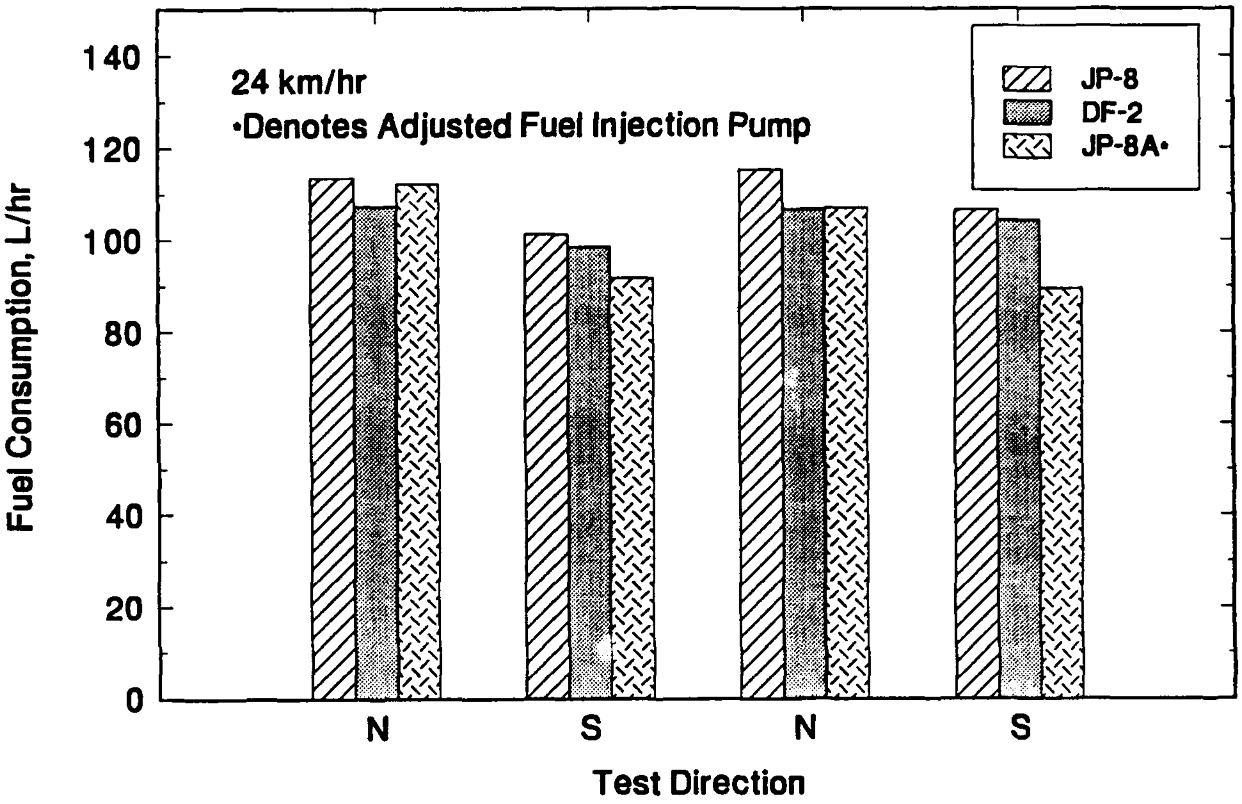

Figure 12. M88A1 fuel consumption — DF-2 to JP-8 conversion

are shown in Fig. 13. In general, the actual vehicle speeds were greater than the target speed. The fuel-consumption rate with JP-8 at 24 km/hr (15 mph) is generally greater than DF-2 with the unadjusted pump. The fuel-consumption rate with the adjusted pump appears to be lower than with the unadjusted pump and similar to DF-2.

The M88A1 vehicle performance at 40 km/hr (25 mph) was significantly affected by the test section grade. The target speed appears to have been near the maximum level road speed of the test vehicle while operating on JP-8 with the unadjusted fuel injection pump. Some of the speed variations were a result of the transmission range attained on the graded portion of the test section. Fig. 14 is the fuel-consumption rate data for a nominal vehicle velocity of 40 km/hr (25 mph). Higher fuel-consumption rates are shown for the northerly direction, except for the first DF-2 evaluation. The speed deviations for the M88A1 vehicle from the target 40-km/hr (25-mph) test speed are shown in Fig. 15. Note that Fig. 15 shows that the vehicle could not attain the test speed utilizing JP-8 with an unadjusted fuel injection pump. The first northerly

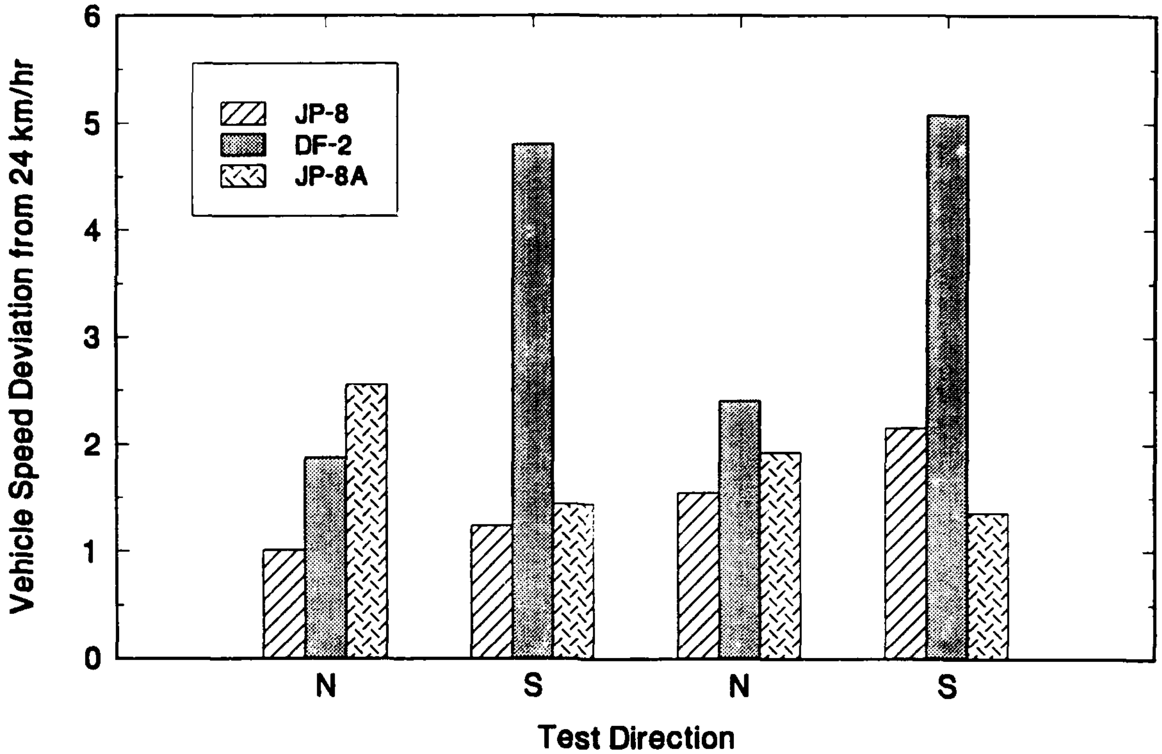

Figure 13. M88A1 vehicle speed deviations — DF-2 to JP-8 conversion

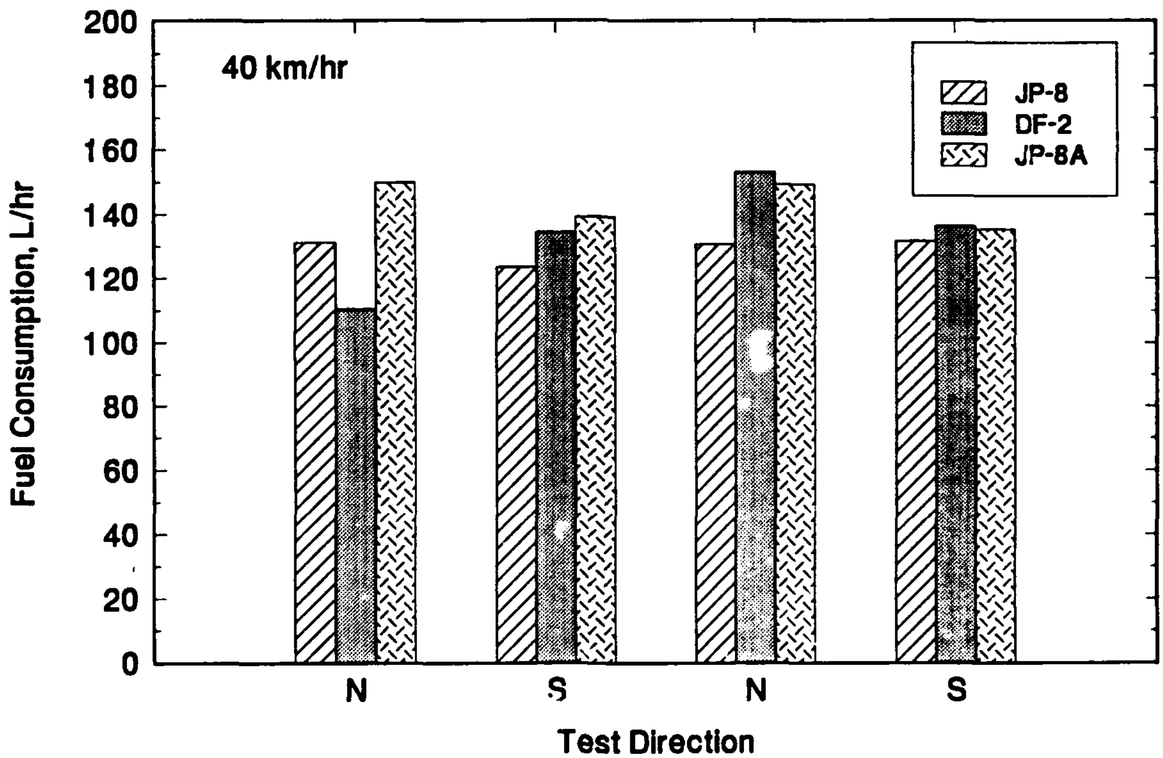

Figure 14. M88A1 fuel consumption — DF-2 to JP-8 conversion

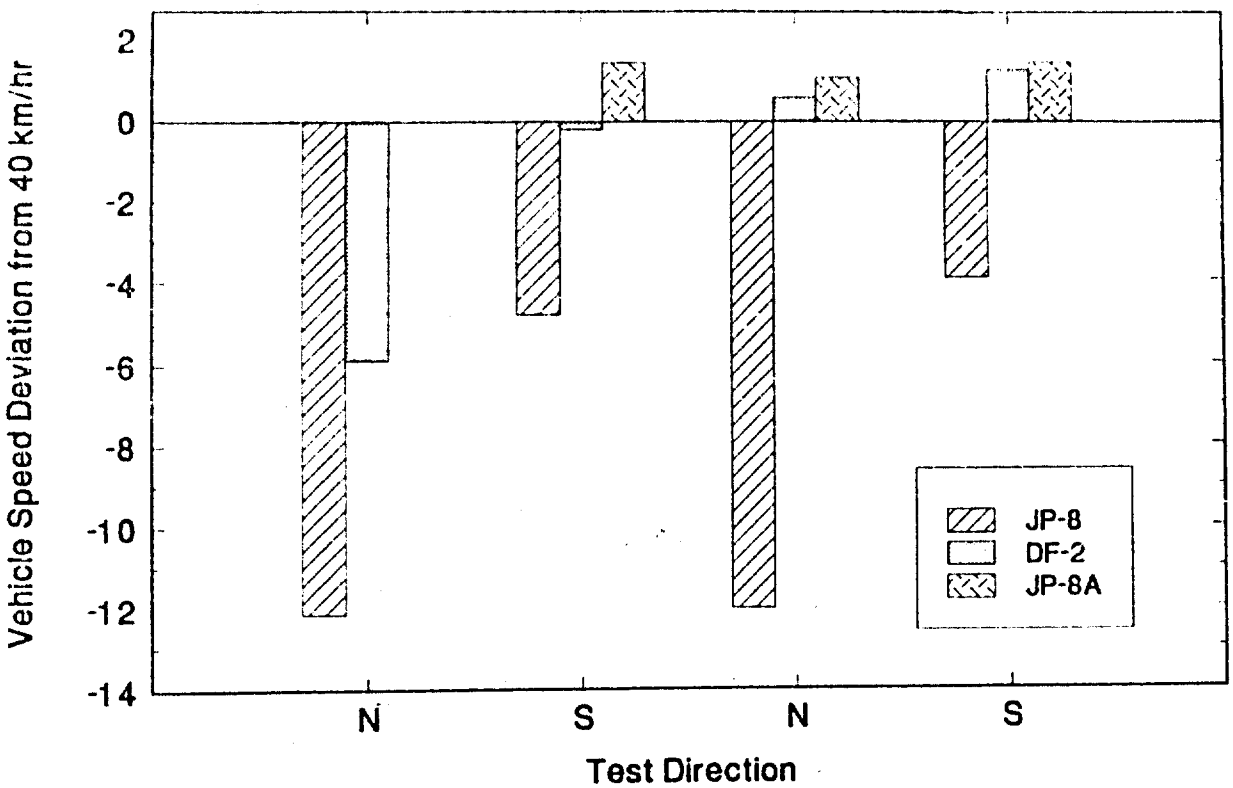

Figure 15. M88A1 vehicle speed deviations — DF-2 to JP-8 conversions

run with DF-2 also was below the target test speed. The data suggest that the fuel-consumption rate with JP-8 in the unadjusted fuel injection pump was affected by pumping losses in the injection pump, as reflected by the vehicle speeds attainable on the test section. The net effect of the fuel injection pump adjustment, with JP-8, appears to be increased fuel-consumption rate combined with increased vehicle speed along the graded test section.

In order to normalize the consumption rates and speed variations, fuel economy values were calculated. The results are expressed in liters/km (gallons per mile), with higher numerical values indicating greater fuel usage. The results for the nominal 24-km/hr (15-mph) vehicle speed are shown in Fig. 16. The data suggest that the fuel economy within each fuel and direction appears consistent. At 24 km/hr, the vehicle appears to require more fuel to negotiate the test section with JP-8 than DF-2, both with and without the pump adjustment. The pump adjustment does appear to somewhat improve the fuel economy with JP-8.

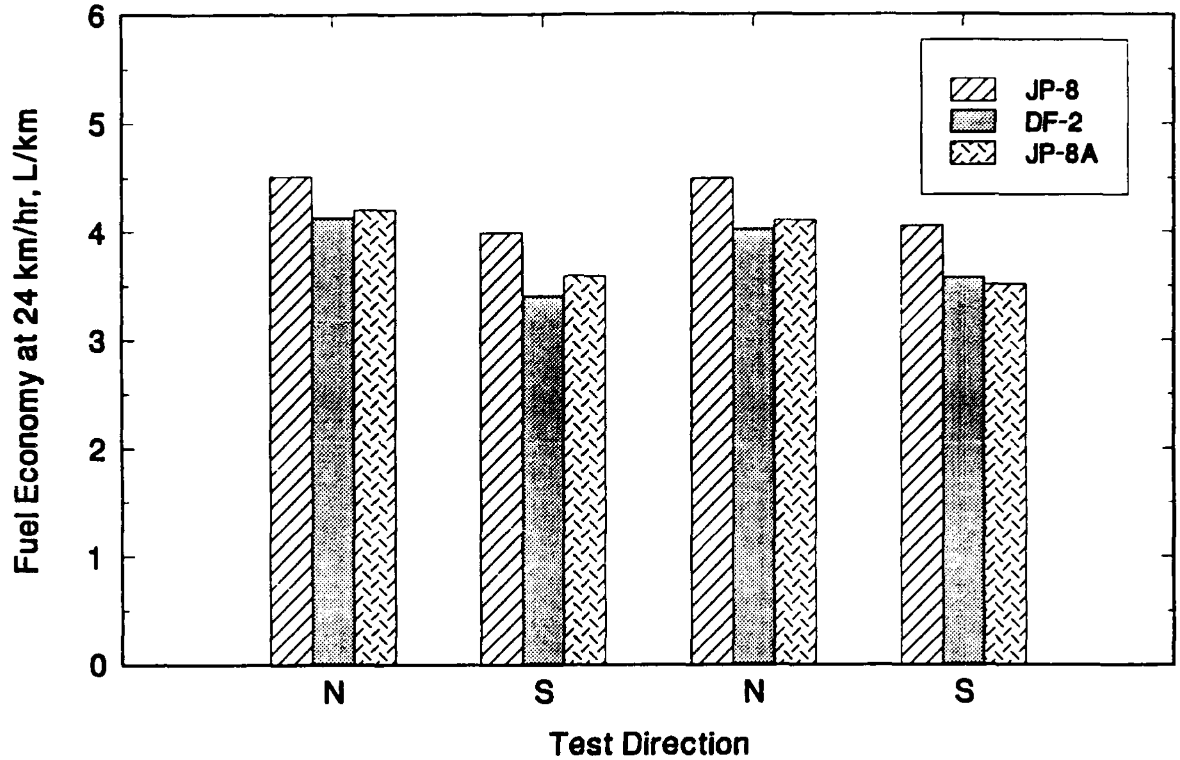

Figure 16. M88A1 fuel economy — DF-2 to JP-8 conversion

The fuel-economy results for the 40-km/hr (25-mph) vehicle speed is displayed in Fig. 17. The results appear consistent within fuel and direction, except for the first northerly DF-2 evaluation. This DF-2 data point appears anomalous when compared to the other results. The fuel usage with JP-8 at a nominal 40 km/hr (25 mph) is greater than DF-2 with the unadjusted fuel injection pump, and appears similar to DF-2 with the adjusted pump. The results indicate an improvement in vehicle fuel economy when utilizing JP-8 with the fuel injection pump adjustment.

The fuel-economy deviations for the M88A1 from DF-2 are shown in Fig. 18 for each JP-8 run at both speeds. The difference between the volumetric heat of combustion of the test fuels is shown for reference. With the unadjusted fuel injection pump, the fuel usage with JP-8 exceeds the values expected due to the heating value difference. The northerly run at 40 km/hr (25 mph) shows a large difference, due to the anomalous DF-2 data point. This point was not discarded due to the limited data available. Of interest is the fact that the fuel pump adjustment improved the fuel economy of the M88A1 while utilizing JP-8, approaching the results predictable from

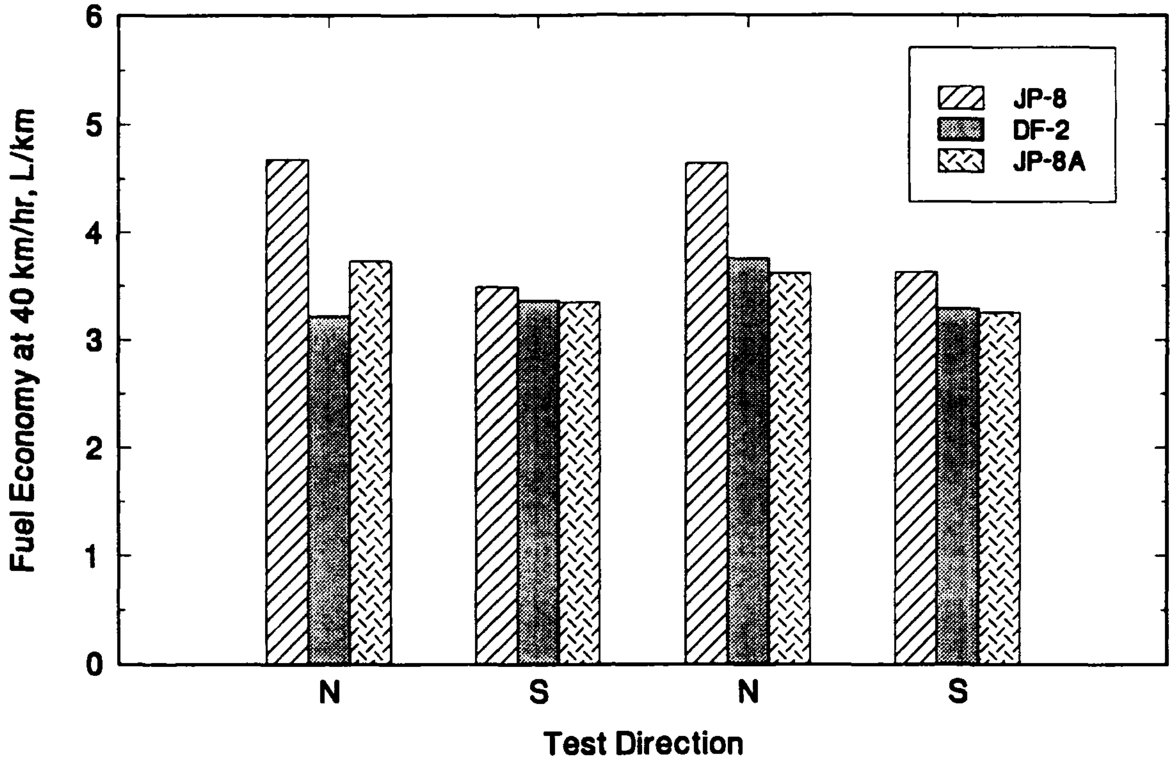

Figure 17. M88A1 fuel economy — DF-2 to JP-8 conversion

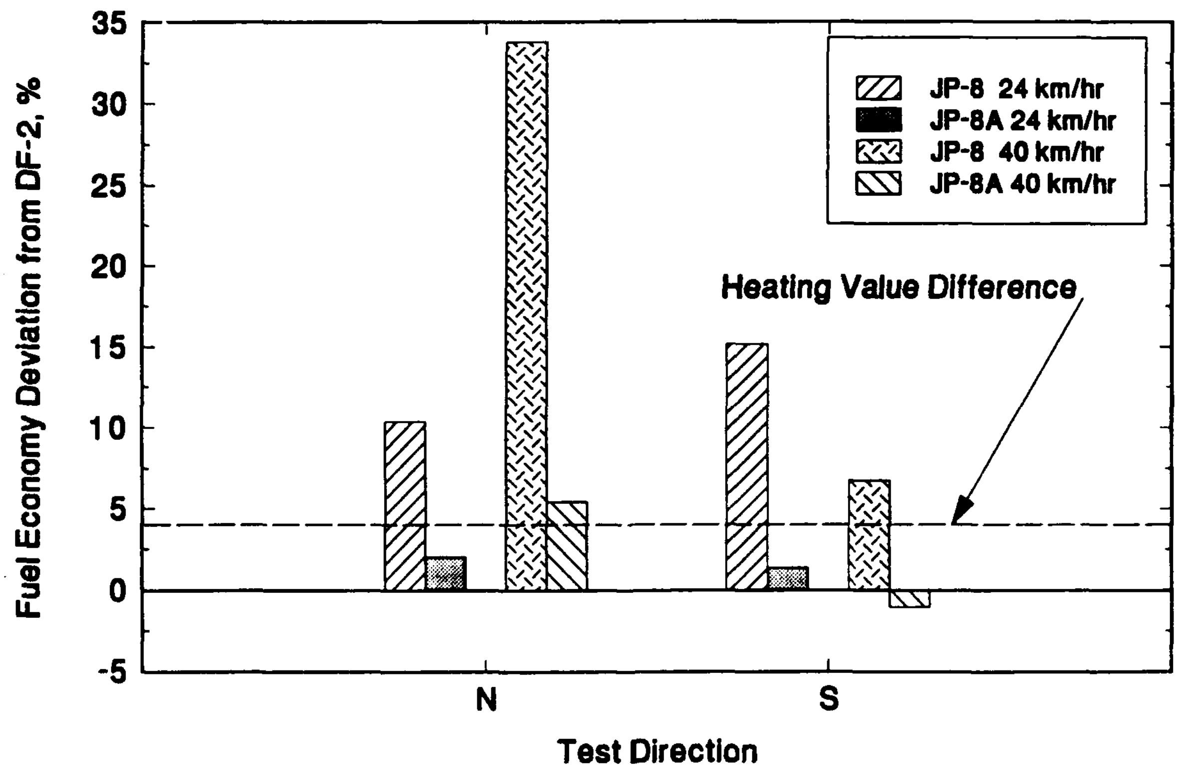

Figure 18. M88A1 fuel-economy deviations — DF-2 to JP-8 conversion

the heating values. It can be speculated that the fuel pump adjustment also effectively advanced the injection timing, accounting for most of the improvement. The directional and overall averages of the fuel-economy deviations are shown in Fig. 19. The two previous measurements with the M88A1 vehicle (1) revealed overall fuel-consumption deviations on the order of 10 to 15 percent for an unadjusted fuel injection pump. The fuel pump adjustment appears to improve the fuel consumption of the M88A1 considerably.

3. Steady-Pull (M1A1HA Tow) Evaluations

The steady-pull evaluations with the M88A1 vehicle towing an M1A1HA main battle tank were also performed on the 3218-meter (2-mile) test section with a slight south-to-north grade. Noteworthy is the speed attained and the resulting fuel consumption for the 3218-meter (2-mile) pull. The vehicle speeds with the M1A1HA in tow are shown in Fig. 20 for the two directions. The towing speeds for the M88A1 vehicle with JP-8 are slower than DF-2 for both the unadjusted and adjusted fuel injection pump evaluations. Although the adjusted pump provides more JP-8 to the engine, no improvement in towing performance is noted as a result of the fuel injection pump adjustment.

The fuel-consumption rates for the evaluations are shown in Fig. 21 for both test section directions. The M88A1 exhibits an effectively higher JP-8 fuel-consumption rate with the adjusted fuel injection pump. When the fuel economy is evaluated, as in Fig. 22, the M88A1 uses considerably more fuel with the adjusted pump. It appears the extra JP-8 consumed by the vehicle is not effectively converted to work when towing the M1A1HA.

The fuel-economy deviations for the M88A1 from DF-2 are shown in Fig. 23 for both course directions. The difference between the heating values of the test fuels is shown for reference. The JP-8 fuel-economy deviation for the vehicle with an unadjusted fuel injection pump is approximated by the heating value difference of the fuels. While the adjusted fuel injection pump with JP-8 shows a fuel-economy deviation greater than what could be predicted from the fuel heating values and the pump flow increase. These effects are opposite of the results obtained when the M88A1 was performing solo.

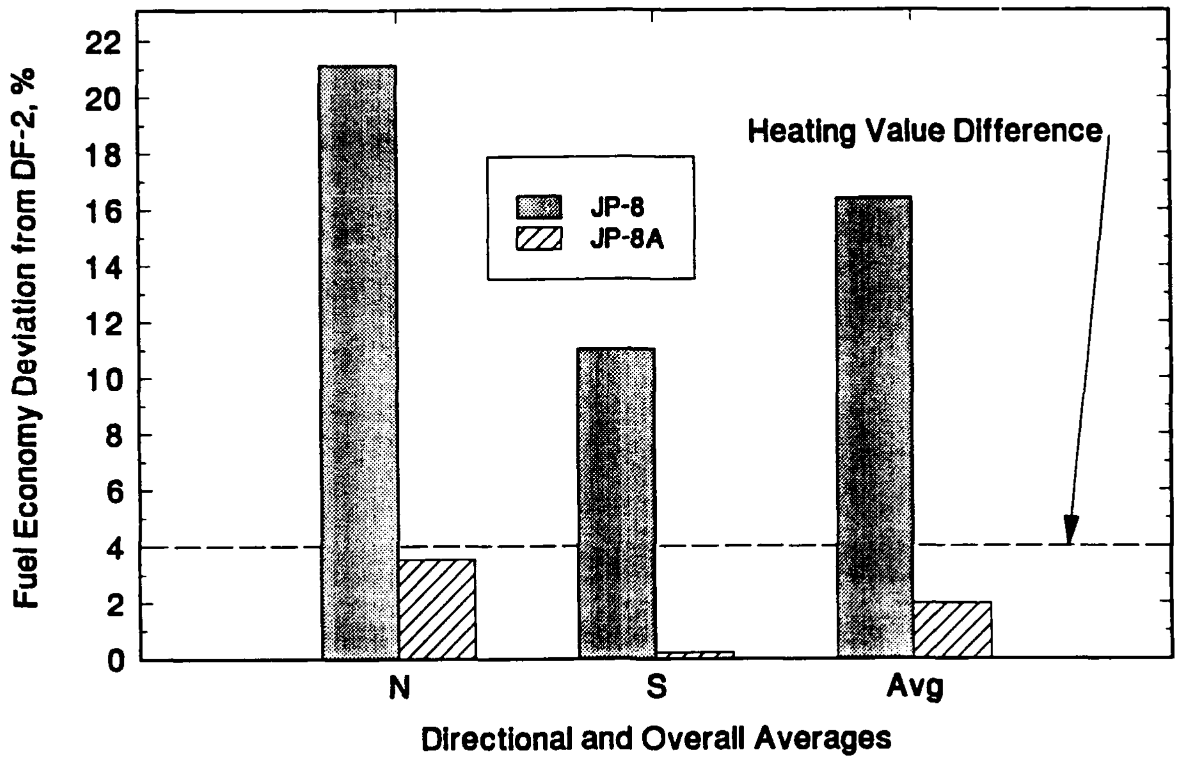

Figure 19. M88A1 overall fuel-economy deviations — DF-2 to JP-8 conversion

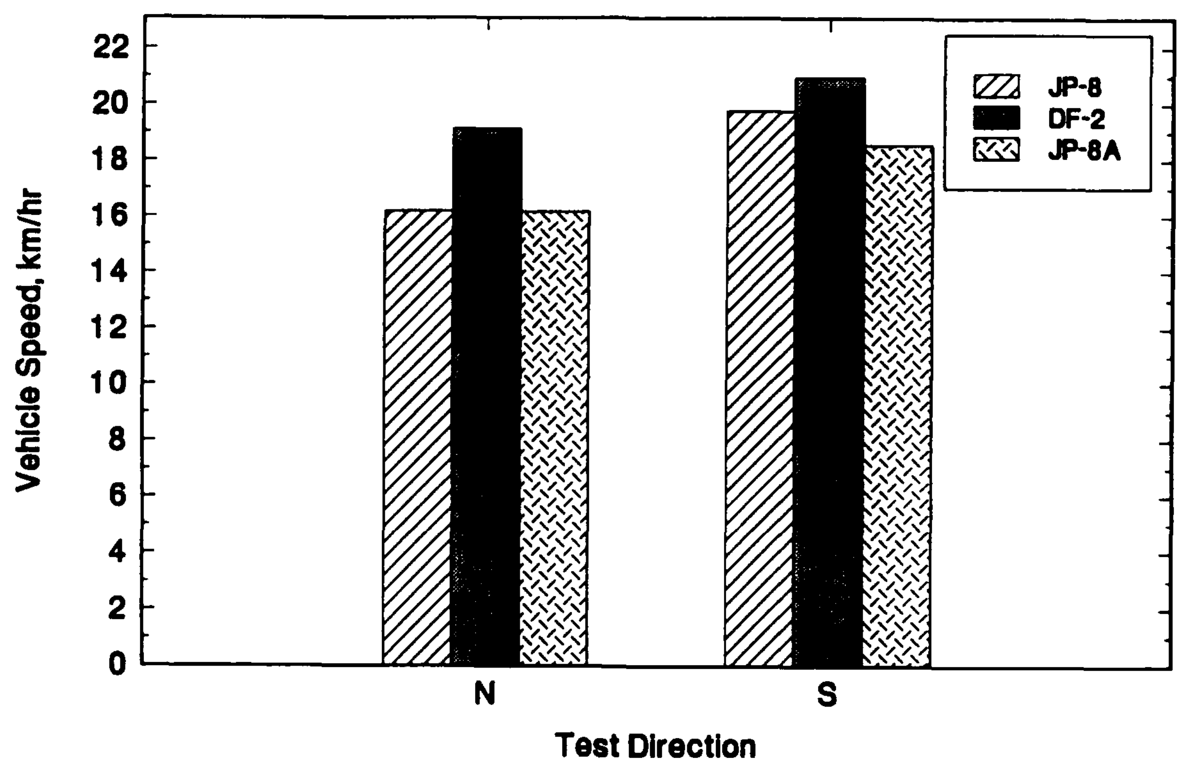

Figure 20. M88A1 steady-pull vehicle speeds — DF-2 to JP-8 conversion

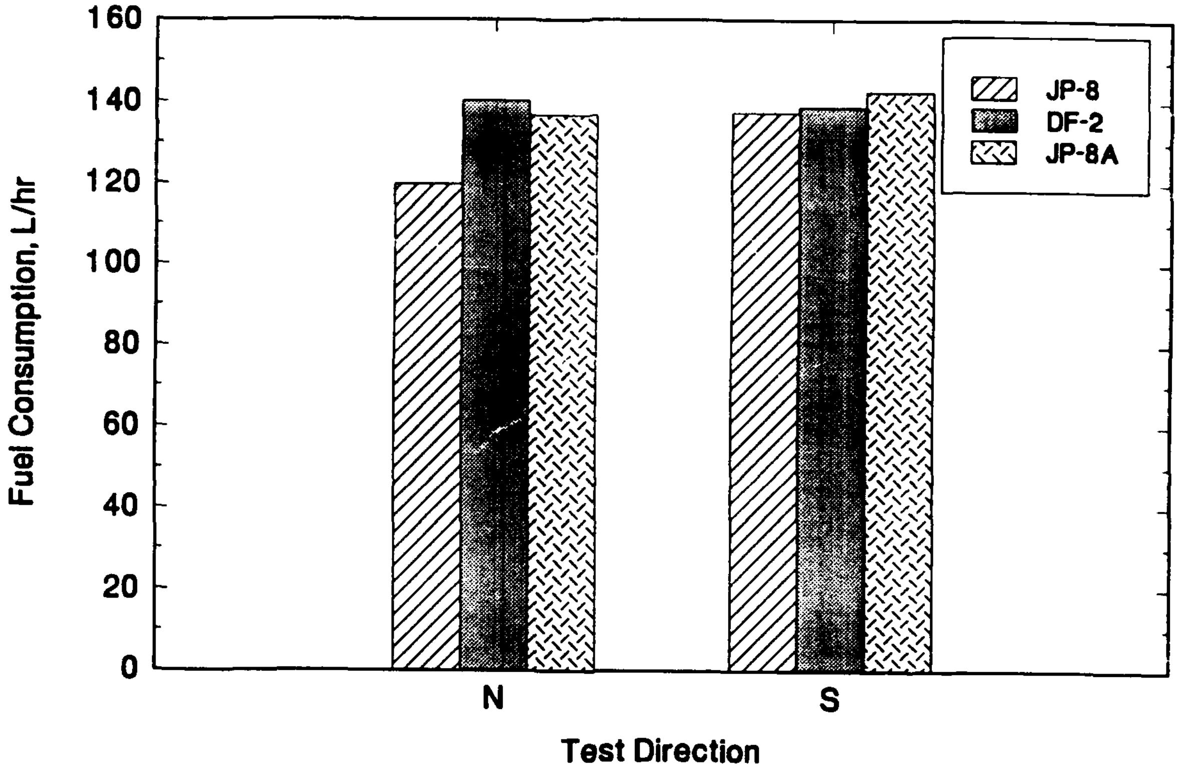

Figure 21. M88A1 steady-pull fuel consumption — DF-2 to JP-8 conversion

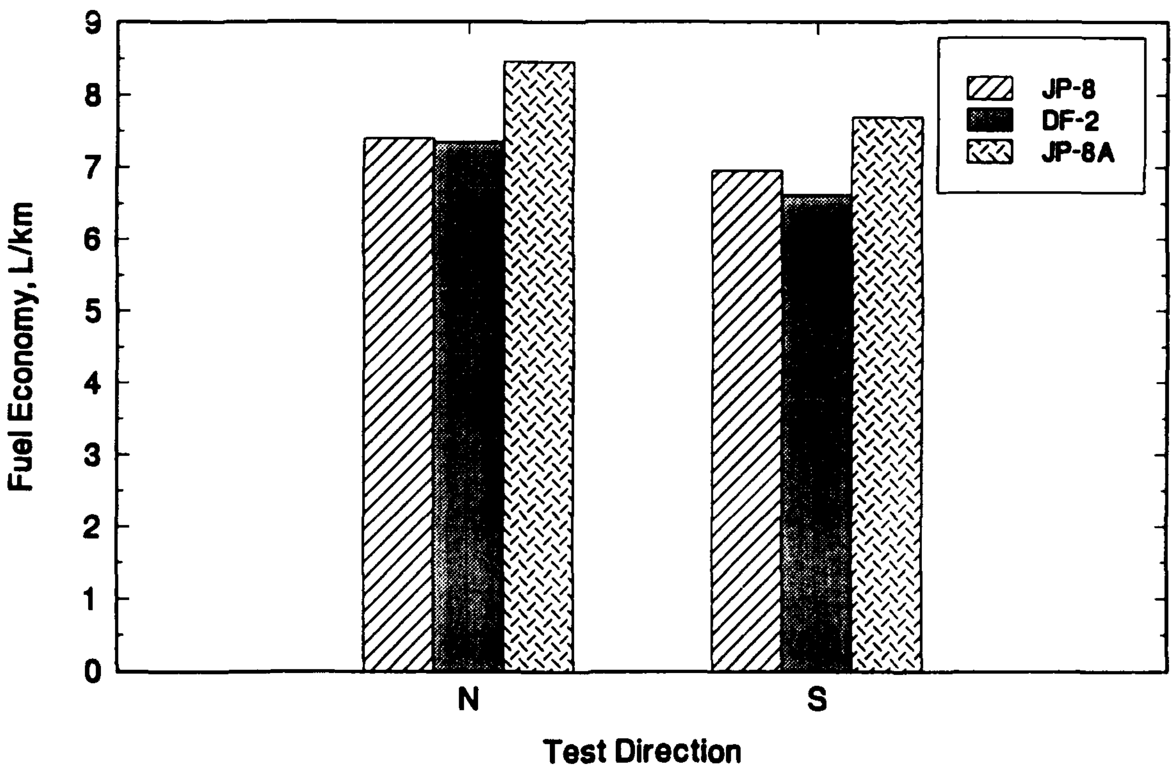

Figure 22. M88A1 steady-pull fuel economy — DF-2 to JP-8 conversion

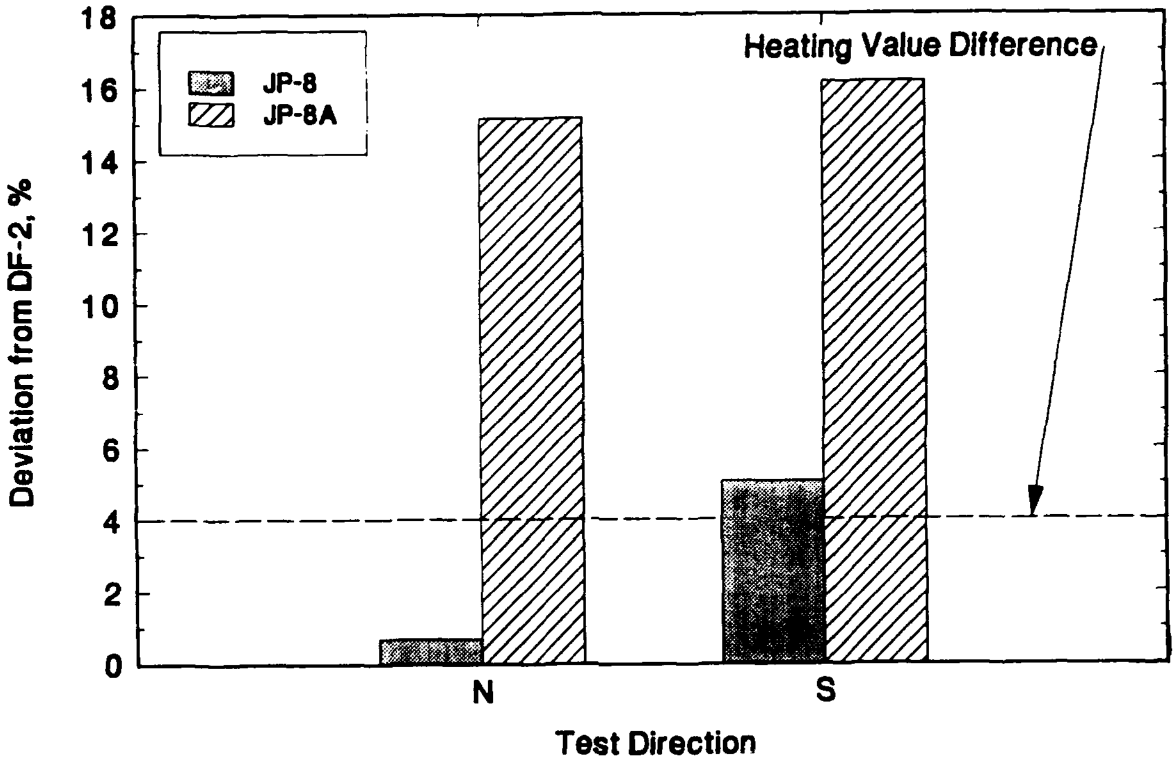

Figure 23. M88A1 steady-pull fuel-economy deviations — DF-2 to JP-8 conversion

A comparison of the energy consumption for performing the towing evaluations is shown in Fig. 24. Of interest is the similar energy consumption between the DF-2 and the unadjusted fuel injection pump JP-8 evaluations. Adjustment of the fuel injection pump for increased JP-8 flow results in increased energy consumption and thermal efficiency penalties. While towing the M1A1HA, the increased flow of the fuel injection pump with JP-8 results in higher fuel consumption without any towing performance improvement.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The following conclusions were reached for the M998 HMMWV and M977 HEMTT vehicles:

- Acceleration times increased 11.5 percent for the M998 and 4.6 percent for the M977 for the speed range evaluated when utilizing JP-8 fuel as compared to DF-2 fuel.

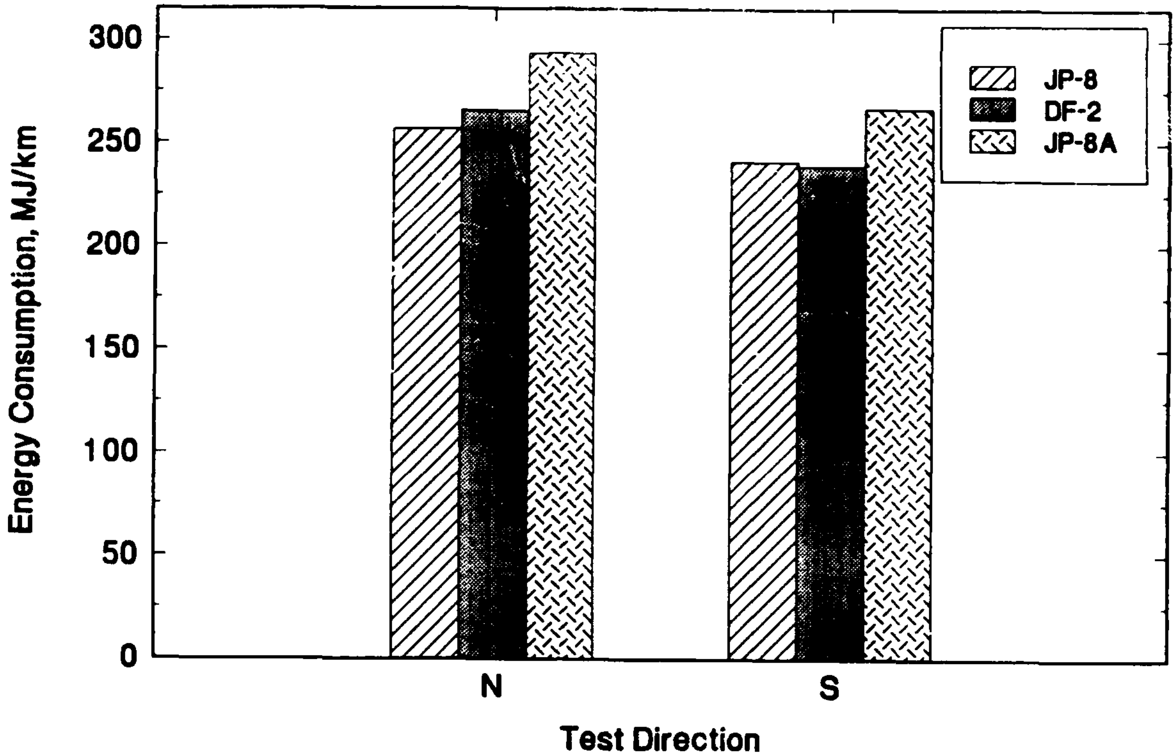

Figure 24. M88A1 steady-pull energy consumption — DF-2 to JP-8 conversion

- An averaged 2-percent increase in fuel consumption was evident with JP-8 at all speeds for both vehicles, except during the 48-km/hr (30-mph) steady-state evaluations on the M998 HMMWV. The 48-km/hr evaluation showed a 2-percent fuel-consumption decrease with JP-8 fuel. The increase in fuel consumption with JP-8, however, was less than predicted by the heating value difference between the two fuels.

The following conclusions were reached for the M88A1 Recovery Vehicle:

Nontowing Tests

- The fuel-consumption rate, liter/hr (gal./hr), at nominal 24 km/hr (15 mph) with JP-8 when utilizing injection pump adjusted to TM specifications was higher.

- Fuel pump adjustment appears to lower fuel consumption with JP-8 at 24 km/hr (15 mph) to equivalent DF-2 levels.

- At nominal 40 km/hr (25 mph), JP-8 with the TM pump calibration reveals lower fuel-consumption rates than DF-2, probably due to pumping losses in the injection pump. The vehicle would not attain the target test speed.

- The injection pump adjustment resulted in improved vehicle performance with fuel-consumption rates equivalent to DF-2.

- Fuel-economy results [liter/km (gal./mile)], which normalize the data for test speed, show improvements in vehicle fuel economy with JP-8 (comparable with DF-2), at both test speeds due to the fuel pump adjustment.

- When compared to the heating value difference between DF-2 and JP-8, the *fuel pump adjustment improves the fuel economy of the M88A1 operating on* JP-8 significantly.

Towing Tests

- No improvement in towing speed of an M1A1HA is noted after the fuel pump adjustment with JP-8. Towing speeds are lower with JP-8 in both cases compared to DF-2.

- The fuel usage with JP-8 [liter/km (gal./mile)] and energy consumption [MJ/km (Btu/mile)] shows significant increases due to the fuel pump adjustment. During the towing of the M1A1HA, the M88A1 appeared to suffer a thermal efficiency penalty due to the fuel injection pump adjustment.

- The net result of the fuel injection pump adjustment with JP-8 was to improve the individual vehicle performance and fuel economy. Even though fuel

consumption in the M88A1 increased, while towing the M1A1HA main battle tank, the M88A1 did not show an improvement in vehicle performance.

B. Recommendations

The following recommendations are made:

- Further investigation of the fuel injection pump adjustment with JP-8 is warranted.

- Effects of worn fuel injection pump components and lower fuel viscosity of JP-8 appear to alter the effect of the pump adjustment. An evaluation should be performed with a new/rebuilt injection pump.

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FORT SCHAFTER HI 96858-5100

CINC
US SPECIAL OPERATIONS COMMAND
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CDR
US CENTRAL COMMAND
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HQ, EUROPEAN COMMAND
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Department of the Navy

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ALEXANDRIA VA 22304-6180

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COMMANDING GENERAL
USMC RD&A CMD
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H&S BATTALION
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WARFIGHTING CENTER
QUANTICO VA 22134-5010

Department of the Air Force

HQ, US AIR FORCE
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WASHINGTON DC 20330

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DET 29
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DEPT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
AWS-110 1
800 INDEPENDENCE AVE, SW
WASHINGTON DC 20590

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION 1
LEWIS RESEARCH CENTER
CLEVELAND OH 44135

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